A STUDY OF THE CAMBRIAN-DEVONIAN CONTACT AT THE FRONT OF THE MOUNTAINS IN BOW VALLEY, ALBERTA.

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A STUDY OF THE CAMBRIAN-DEVONIAN CONTACT AT THE FRONT OF THE MOUNTAINS IN BOW VALLEY, ALBERTA.

by

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INTRODUCTION

INTRODUCTORY STATEMENT

Within recent years the search for oil and gas has led to the development of several promising structures situated in limestone inliers of the foothills belt of Southern Alberta. In many of these structures there were indications that oil-bearing horizons might be found in strata of Devonian age, but although showings were encountered, no producing horizon of any importance has so far been penetrated. In some wells drilling operations were continued down through the Devonian and into the Cambrian rocks lying beneath, in the hope that these strata would prove to be oil-bearing. As a result of such developments the problem of the Cambrian-Devonian contact along the front of the mountains has become a matter of considerable importance.

In the spring of 1941 it was suggested to the writer that the Cambrian-Devonian contact at the front of the mountains in Bow valley be investigated as a thesis assignment. Subsequently, in October 1941, the writer spent several days examining the contact and measuring the exposed section below it, and collecting samples therefrom. The results of that work are embodied

in this report.

EARLY EXPLORERS IN THE REGION

The earliest known exploratory expedition into this region was that of David Thompson and Duncan McGillivray, who in November, 1800, ascended Bow river from the mouth of Ghost river, to a point near the present location of the town of Exshaw (Morton, 1929, Appendix, p. 9). Thompson climbed a mountain nearby and describes in his journal "a boundless view to the east, and on the west a sea of hills and peaks" (Coues, 1897, p. 704). In 1840 the Rev. R. T. Rundle entered the mountains through Bow river gap to do missionary work among the Stoney Indians (Wesleyan Missionary Notices, 1841-2-3; cited by Warren, 1927, p. 1). In August, 1858, Dr. James Hector, geologist accompanying Captain Palliser's expedition, passed through Bow river gap on his way up the river from Bow Fort, and camped at Lacs des Arcs, west of Exshaw. It was Dr. Hector who made the first contribution to the geology of Bow valley, but he apparently did not examine the rocks at the front of the mountains (Palliser, 1863, p. 99). Later, around 1880, the first surveyors engaged in locating a route for the Canadian Pacific Railway, entered the mountains at this point.

PREVIOUS GEOLOGICAL WORK

In 1886, R. G. McConnell, of the Geological Survey of Canada, explored the Rocky Mountains and measured a section near the 51st parallel. McConnell recognized rocks of Cambrian age at the front of the mountains and realized that they were overlain by Devonian strata. He also observed and described the great fault at the base of the range, by which Cambrian rocks are thrust over the Cretaceous of the foothills (McConnell, 1886, p. 33). Since McConnell's time no detailed study has been made of the Cambrian-Devonian contact at this place.

ACKNOWLEDGMENTS

The writer wishes to acknowledge his appreciation of the generous assistance and kindly advice received from the staff of the Department of Geology. Thanks are especially due to Dr. P. S. Warren, who outlined the project, and under whose supervision this thesis was written, for helpful suggestions and for permission to use many books and publications from his personal library. Acknowledgments are also due to Dr. J. A. Allan and Dr. R. L. Rutherford for suggestions and criticisms, and for the use of various publications.

The writer wishes to express his thanks to Dr.

Charles Deiss of Montana State University, who identified the fossils collected in the field, and whose publications were used as the main source of information on the Cambrian stratigraphy and palaeontology of the Cordilleran trough.

Finally, the writer desires to acknowledge his indebtedness to Mr. D. B. Layer and Mr. C. H. Templeton, whose interest and cooperation added greatly to the amount of information obtained in the field.

The writer regrets that the following acknowledgments were inadvertently omitted during the typing of this thesis. The McColl-Frontenac Oil Co., Ltd., supplied the writer with a log of their Moose Mountain No. 1 well, and the Petroleum and Natural Gas Conservation Board gave assistance in the form of detailed information on the samples from the same well. For these services the writer expresses his appreciation.

CHAPTER II

DESCRIPTIVE GEOLOGY

GENERAL DESCRIPTION OF SECTION

The section studied by the writer is well exposed at the front of the mountains in Bow valley, 55 miles from Calgary, on the north side of the Banff highway just west of Kananaskis (see map, fig. 1). The Cambrian limestone is first encountered in the valley about half a mile west of Kananaskis station, although it extends farther east on the mountains to the north and south. The exposed section consists of greyish colored limestone, dolomite and arenaceous dolomite and has a measured thickness of 1,627 feet.

Where first encountered at the eastern limit of the exposure the Cambrian rocks stand almost vertical. Above this the inclination gradually lessens until at the top of the section studied by the writer the beds dip uniformly westward at an angle of about 45 degrees. There is no visible folding or faulting in the beds in the river valley. The thrust fault at the base of the range, described by McConnell, is not apparent in the valley but can be plainly seen on the mountain to the north.

For the most part the section is very homogeneous,

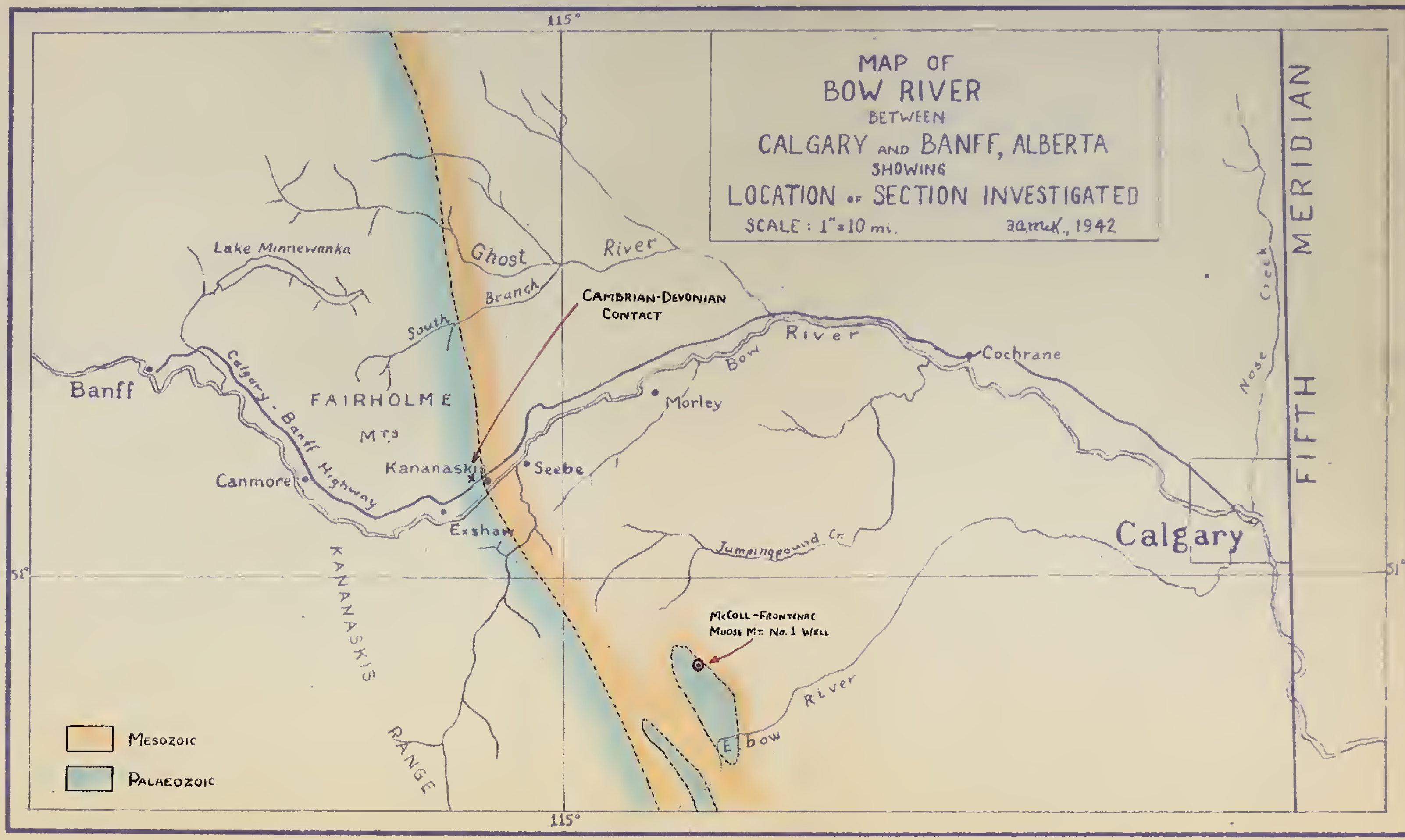

Figure 1. Location Map.

consisting mainly of dark grey fine grained dolomitic limestone. Notable small variations are, however, apparent. Three well defined bands of very pure dense light grey limestone, each about 50 feet thick, occur in the lower half of the exposed section. The quarry and lime kiln of the Loder Lime Company are situated on the lowest of these limestone bands.

Fossils are very scarce except in the uppermost beds of the section. The only fossil remains found were poorly preserved trilobite fragments, brachiopods and fucoidal markings which occur on the weathered surfaces of a thin-bedded hackly-weathering impure limestone horizon about 195 feet from the top of the section.

Above the fossil horizon the rock changes gradually into a light buff colored arenaceous dolomite characterized by the presence of glauconite. This dolomite horizon is about 20 feet thick and is easily traced as a light colored band running along the escarpment which forms the eastern face of the mountain. Throughout a thickness of about 50 feet above the buff colored band the rock is a thin-bedded dark grey limestone which is terminated above by a sharply defined contact upon which lies the massive black saccharoidal dolomitic limestone of the lower part of the Minnewanka formation. This contact was taken as the upper limit of the measured section.

Figure 2. Cambrian-Devonian contact (c) from highway $\frac{1}{4}$ mile west of Loder Lime Company plant.

Figure 3. Base of Lower Minnewanka (m), overlying Middle Cambrian beds (c), showing location of fossil horizon (x).

Photos by M.B.B. Crockford, 1941

Figure 2

Figure 3

FIELD WORK

The study of the section was begun at the lime kiln on the north side of the highway about three quarters of a mile west of Kananaskis. From this point a preliminary traverse was made up the eastern slope of the mountain. Since the purpose of the investigation was to define the Cambrian-Devonian contact, the traverse was not carried up into the Lower Minnewanka formation which is Devonian in age and easily recognized by the presence of reefs of fine structureless corals.

Examination of the lower beds of the Minnewanka formation revealed that an abrupt lithological change occurs immediately below the lowest coral horizon, where the rock changes from massive black saccharoidal limestone to fine grained thin-bedded dark grey limestone. Below this contact no corals were found. Furthermore, although there was no evidence of an unconformity, this contact appeared to be the only indication of a break in sedimentation, since any lithological changes which occur between it and the trilobite horizon are gradational.

From these observations it seemed reasonable to consider the contact at the base of the Minnewanka formation as the upper limit of the section to be investigated. The fact that this contact is well defined

and easily located at almost any point along the face of the mountain facilitated the study of the upper part of the Cambrian section.

Accordingly, measurements were begun at the base of the Minnewanka formation and continued down through the Cambrian section to the farthest east exposure along the highway. Wherever possible, thicknesses of beds were measured directly with a fifty foot tape. Where direct measurements were impossible, the tape was used to measure traverse distances, and a small hand level was used to measure dips and slope angles. Thicknesses of beds were then computed from the data thus obtained. The actual thickness of the exposed section of Cambrian below the Minnewanka formation was calculated to be 1,627 feet.

Since the age of the upper 195 feet of the section must be regarded as questionable, particular care was taken in measuring and sampling this zone in order to detect lithological variations and if possible to find some evidence of fossil remains.

CHAPTER III

THEORIES OF DOLOMITIZATION

GENERAL STATEMENT

Most of the rock in the Cambrian section contains a considerable proportion of dolomite, and the degree of dolomitization varies from one horizon to the next. The problem of the origin of the dolomite is concerned with environmental conditions during deposition and diagenesis of these rocks.

Much has been written on the different methods by which dolomite may have been formed, and the writer proposes to present here a review of the literature on the subject, as well as a reasonable explanation of the processes and environmental conditions which would account for the dolomitization in the Cambrian rocks dealt with in this investigation.

DEFINITION OF DOLOMITE

The mineral dolomite is considered to be a chemical compound composed of the carbonates of calcium and magnesium in equi-molecular proportions. The accepted chemical formula is $CaMg(CO_3)_2$, in which $CaCO_3$ = 54.35% and $MgCO_3$ = 45.65%. Pure dolomite is seldom found in nature. Calcium carbonate is often present in excess quantities, and iron and manganese

frequently replace the magnesium.

The term "dolomite" is sometimes incorrectly applied to limestones which carry an appreciable amount of magnesium carbonate. In this paper the term "dolomite" is applied only to material which reacts micro-chemically as dolomite. The term "dolomitic limestone" refers to limestone which has been partially dolomitized and which therefore contains an appreciable amount of dolomite.

THEORIES OF ORIGIN OF DOLOMITE

There are several theories regarding the origin of dolomite, but all dolomites within the scope of this report may be classed under two general headings as follows:

(a) Pre-emergent dolomites

(b) Post-emergent dolomites

Pre-emergent Dolomites

These are dolomites formed in the sea, either by direct precipitation or by reactions within the limy sediments on the sea floor after deposition and before lithification.

Dolomites Formed by Direct Precipitation

The fact that many dolomites possess an extremely fine and uniform grain has led some writers to believe

that they represent chemical deposits. Daly (1909, p. 167) describes the Precambrian dolomite of the Rocky Mountains region along the 49th Parallel, in which the fineness and uniformity of grain are very persistent both stratigraphically and laterally. He believes this points to a chemical origin, and further postulates that most pre-Devonian dolomites were deposited as direct chemical precipitates in a nearly limeless ocean. According to Daly the calcium : magnesium ratio of the pre-Devonian ocean was comparatively low because the land masses in Precambrian and early Palaeozoic time consisted of crystalline igneous rocks which supplied only a relatively small amount of calcium to the sea water. Daly also states that the evolution of scavenger forms had only begun, and that organisms after death were left and allowed to decay on the sea floor. Such organic decay produced large amounts of ammonium carbonate which acted as a precipitating agent.

That organic material in the process of decay will precipitate carbonates was demonstrated experimentally by Fischer (cited by Van Tuyl, 1914, p. 300) who placed decaying organisms in sea water and obtained a precipitate composed of 95.45 percent calcium carbonate and 5.55 percent magnesium carbonate. However, neither increasing the concentration of the sea water and of the organic

matter nor increasing the temperature served to raise the magnesium content of the precipitate enough to approximate the composition of dolomite. Steidtmann (1911, p. 330) points out that while it is true that decaying marine organisms generate ammonium carbonate which would act as a precipitant, such decay also produces carbonic acid which would tend to keep carbonates in solution. Corrosion of calcareous remains by the action of carbonic acid is regarded as sufficient to prevent the accumulation of calcareous ooze on the sea bottom at any depth greater than 2,730 fathoms (Steidtmann, 1911, p. 331). There is little direct evidence supporting the view of primary precipitation of dolomite.

Wallace (1927, p. 67) reports a discussion with reference to the Lorraine Muschelkalk, which has been assigned a physico-chemical origin, formed inshore from calcium and magnesium carbonates which were transported as colloids stabilized by protective organic colloids and finally deposited in intimate mixture as a fine precipitate which would subsequently crystallize. The mixed carbonates of calcium and magnesium would probably form first, and the formation of dolomite would occur during lithification, after moderate pressures applied over a long period of time had permitted sufficient molecular mobility to bring about the gradual combination

of the carbonates. Definite proof of such a process is lacking.

Experimental attempts to form dolomite have met with very little success. Van Tuyl (1914, p. 299) mixed standardized solutions of the bicarbonates of calcium and magnesium in molecular equivalent proportions to give the same ratio of calcium carbonate to magnesium carbonate as exists in pure dolomite. Evaporation was carried out at ordinary temperatures and pressures for a period of one month. A precipitate of calcium carbonate began to form first, after which hydrous magnesium carbonate ($MgCO_3.3H_2O$) was deposited, but no dolomite was formed. Negative results were still obtained when a crystal of pure dolomite was placed in the solution before evaporation was commenced. The crystal did not grow and no dolomite was formed. Similarly unsuccessful was the attempt to crystallize the double carbonate of calcium and magnesium from a solution obtained by the action of carbonated water on normal dolomite.

Mitchell (1923, p. 1887) succeeded in forming small amounts of a substance closely approximating dolomite in composition. He used 500 cc. of artificial sea water containing no magnesium chloride or calcium carbonate, into which solutions of 1/25 N magnesium chloride and saturated calcium bicarbonate were allowed to enter drop by drop from burettes on opposite sides of the beaker

until 100 cc. of each had been added. The solution was then made alkaline by adding 1/20 N sodium carbonate. After six hours a precipitate appeared, which doubled in bulk in a week. The particles in this precipitate were too small to permit accurate determination of optical properties beyond the fact that the refractive index was greater than 1.69 and the birefringence was very strong, but the chemical composition was approximately that of dolomite.

The chief difficulties involved in investigating the origin of dolomite by experimental methods are encountered in attempting to duplicate the natural effects of combinations of temperature, pressure and time in the laboratory.

Dolomites Formed by Reactions in the Sediments on the Sea Floor

According to many authorities, most marine dolomites have been formed after deposition and before lithification of the limy sediments on the sea floor. Dolomitization has occurred almost simultaneously with the formation of the limestone after the sediments were deposited. This is known as contemporaneous or pene-contemporaneous dolomitization. The mechanics of contemporaneous dolomitization are not well understood. It is possible that the process has occurred in different ways.

(a) Dolomitization by Marine Leaching: Since calcium carbonate is more soluble than magnesium carbonate, it is possible that the magnesium carbonate content of unconsolidated ocean-floor sediments containing both substances could be enriched by marine leaching which would tend to remove the calcium carbonate and leave the magnesium carbonate. The process would probably occur most rapidly in shallow protected lagoons, since the solubility of calcium carbonate is increased by a rise in the salinity of the water. To account for the accumulation of any great thickness, continual slow subsidence must also be postulated. Steidtmann (1911, p. 332) reports the work of Högbom, who carried out experiments on the clay marl of Upsala. The original marl, which contained 18% calcium carbonate and 1.3% magnesium carbonate, was washed with carbonated water. It was found after the washing that more than 50% of the calcium carbonate had been removed, while the loss of magnesium was negligible.

The smaller the calcium content of the sea water compared with magnesium the more effective would be the process of leaching. Since it appears reasonable, as postulated by Daly (1909, p. 153) and Steidtmann (1911, p. 323, 392) that the oceans of early Palaeozoic time had a comparatively low calcium : magnesium ratio, it follows

that the process of dolomitization by marine leaching was probably more important then than at the present time.

If the sediments were partially lithified at the time of leaching, cavities would probably result from the removal of the calcium carbonate, but in unlithified sediments no porosity would develop.

There are several objections to the theory of dolomitization by marine leaching. There can be no doubt that the leaching process has enriched the magnesium content of some dolomitic limestones, but such limestones must have been fairly rich in magnesium before the leaching began. This theory does not explain the ultimate origin of the magnesium. Nor will this theory give an adequate explanation for the sharp boundaries between many inter-stratified beds of pure dolomite and pure limestone.

(b) <u>Dolomitization by Replacement</u>: The theory of marine dolomitization by replacement of the calcium carbonate in the calcareous ooze on the sea floor by magnesium salts contained in sea water is probably most widely held at the present time (Blackwelder, 1913, p. 607; Van Tuyl, 1914, p. 253; Steidtmann, 1917, p. 431; Tarr, 1919, p. 114; Wallace, 1927, p. 64).

The replacement theory was first advanced by

J. D. Dana in 1843 (cited by Steidtmann, 1911, p. 334) to explain the dolomitization of certain coral reefs in the Pacific Ocean. Dana expressed the view that the dolomite had been formed in sea water at ordinary temperatures, in sheltered lagoons where the salts were highly concentrated. It was suggested that under such conditions carbon dioxide liberated by organic decay in the reef would react with and dissolve some of the calcium carbonate of the reef rock. The calcium carbonate in solution would then react with magnesium salts in the sea water to form magnesium carbonate. Van Tuyl (1914, p. 401) suggests that the chemical equations for such a process would be as follows:-

(1) $MgCl_2 + CaCO_3 \longrightarrow CaCl_2 + MgCO_3$

(2) $MgSO_4 + CaCO_3 \longrightarrow CaSO_4 + MgCO_3$

Equation (2) has also been called upon to account for the association of some dolomites with gypsum deposits.

The percentage composition of sea water, given in terms of ions, is shown in the following table, compiled from data listed by Clarke (1924, p. 127).

	per cent
Cl	55.33
Na	30.53
SO_4	7.82
Mg	3.76
Ca	1.15
K	0.99
CO_3	0.23
Br	0.16
others	0.03

From this table it can be seen that the proportion of magnesium ions contained in normal sea water is relatively high, and it is to the action of these ions that marine dolomitization by replacement must be attributed.

It is probable that the reactions involved in the solution of calcium carbonate and the formation of magnesium carbonate would be as follows:-

(1) $CaCO_3 + H_2O + CO_2 \longrightarrow Ca(HCO_3)_2 \longrightarrow Ca^{++} + 2HCO_3^-$

(2) $Mg^{++} + HCO_3^- + 2OH^- + H^+ \longrightarrow Mg(OH)_2 + H_2CO_3 \longrightarrow H_2O + CO_2$

(3) $Mg(OH)_2 + CO_2 \longrightarrow MgCO_3 + H_2O$

Wallace (1913, p. 420) in discussing the dolomitization of the Lower and Upper Mottled limestone of Manitoba, sums up the discussion with the following statement:-

> The evidence in the field and laboratory is sufficient to lead one to conclude that the dolomitization is not a subsequent phenomena - due to the percolation of Mg-bearing waters from above through a considerable thickness of limestone along lines of weakness, but took place as a practically contemporaneous process with the formation of the limestone, in the upper layers of the calcareous ooze of the sea bottom.

The details of the process by which the carbonates of calcium and magnesium are combined to form dolomite have not been definitely determined. Nor is it known

whether the double carbonate is formed directly or whether hydrous magnesium carbonate ($MgCO_3.3H_2O$) is first formed and subsequently combined with calcium carbonate, losing its water of crystallization to form dolomite. According to Van Tuyl (1914, p. 401) it is probable that at the time of the reaction each molecule of magnesium carbonate reacts with one molecule of calcium carbonate in solution to form dolomite, which is deposited. Van Tuyl assumes that the equation for this reaction would be as follows:-

$$MgCO_3 + CaCO_3 \longrightarrow CaMg(CO_3)_2$$

The presence of magnesium carbonate in the original sediments, would favor dolomitization. The finer the grain size of the sediments, the more susceptible they would be to dolomitization processes providing the degree of compaction was not high enough to exclude the magnesium-bearing sea water. Carbon dioxide dissolved in the sea water would render the calcium carbonate more soluble, and limy sediments rich in organic remains should therefore be more easily dolomitized than limy sediments in which no organic remains occur.

It is generally agreed that most dolomites are of shallow water origin. But whether concentrated seas are necessary for dolomitization processes has been a matter of considerable controversy. Tarr (1919, p. 114) believes that dolomitization by replacement would be

most likely to occur in broad shallow inclosed seas in which the concentration of magnesium and other salts would be above that of normal sea water. On the other hand, Wallace (1913, p. 421) maintains that dolomitization may occur when the percentage of magnesium is relatively small. In this case, only partial dolomitization would result. Blackwelder (1913, p. 623) in discussing the origin of the Bighorn dolomite of Wyoming, states that the concentration of the magnesium salts in the sea water at the time of dolomitization could not have been more than two or three times as much as in the present ocean because high concentrations of magnesium salts are unfavorable to organic life, the remains of which are found in comparative abundance. But admitting the possibility that dolomitization could occur under conditions of low concentration, it seems reasonable to suppose that it would progress much more rapidly and more completely at higher concentrations.

It is thus reasonable to postulate that conditions favorable to the formation of dolomite would be found in a lagoonal environment, in which the salts would be concentrated. The margin between conditions necessary for the formation of dolomite and those favorable to the formation of limestone is probably a narrow one, and a slight change in salinity would halt the process of dolomitization. Cyclical influxes of normal sea water

into the lagoon would prevent the formation of dolomite until the salinity of the water became high again and the process could be resumed. This would account for inter-stratification of beds of dolomitized and undolomitized rock. Continual slow subsidence must be postulated to account for the accumulation of great thicknesses of such sediments.

The mottling which is evident in many dolomites would represent an incipient stage of dolomitization. This feature is well discussed by Wallace (1913, p. 402) and Van Tuyl, (1914, p. 342). Mottled limestones are of two general types:-

(1) Organic - in which the dolomite patches follow worm castings or fucoidal markings

(2) Inorganic - in which the dolomite patches are irregular in shape and show no relation to any guiding influence.

The presence of dolomitized worm casts in many formations indicates that these rocks were laid down as a very fine ooze. In many cases the dolomitized worm casts are embedded in pure limestone, which suggests either that the worms selected certain types of food material, or that their digestive processes made the casts more susceptible to dolomitization than the surrounding calcareous material.

Wallace (1913, p. 416) believes that mottling in the Ordovician limestones of Manitoba is related to algic

decomposition. Analyses quoted by Wallace show that the amount of MgO in the ash of some algae may be as high as 11.66 per cent. If such algae were buried by calcareous ooze before decomposition began, the magnesium contained in the algae together with magnesium derived from sea water might give rise to local dolomitization.

Van Tuyl (1914, p. 406) describes inorganic mottling as a "selective dolomitization phenomenon". According to him the solutions which caused such dolomitization must have permeated the sediments uniformly, but certain factors such as a variable amount of original magnesium carbonate content, variable amount of organic material, and variable texture, may have made certain areas or layers more susceptible to dolomitization than others.

Post-Emergent Dolomites

These have been formed by processes which acted upon limestone formations after they were uplifted above the sea. This is known as subsequent dolomitization.

Proof that some dolomites are post-emergent in their time of development is found in the fact that they replace limestones adjacent to faults, joints and other lines of weakness. Dolomitization of limestones after emergence, by the action of percolating ground waters is probably of local importance wherever the carbonates of

calcium and magnesium are both orginally present, because of the difference in solubility of the two substances. Dolomite in veins and vugs of limestone formations has undoubtedly arisen in this manner. But although such dolomites are fairly common they represent only a very small percentage of dolomitic formations. Subsequent dolomitization could never account for the accumulation of great thicknesses of pure dolomite, nor could it account for inter-stratification of pure limestone and pure dolomite. Many instances are known in which a thick band of pure dolomite is conformably and regularly overlain by a formation of pure limestone, proving that the dolomite must have been formed before the limestone was deposited. It seems highly improbably that such a condition could have arisen by post-emergent processes.

Summary

Dolomites have probably originated in more than one way. Most dolomites are undoubtedly of marine origin.

There is little evidence that much dolomite has been formed by direct precipitation, and attempts to precipitate dolomite experimentally have not been successful.

It is the opinion of most authorities that the marine leaching theory is not sufficiently adequate to account for the formation of any large amount of dolomite.

It is thought that most dolomites have been formed by a process of replacement of calcium carbonate in the calcareous ooze on the sea floor by magnesium salts contained in sea water, probably in lagoonal environment where the water was shallow and the salts were concentrated. This theory seems to give the most satisfactory explanation for the origin of most dolomites.

Although there is no doubt that some dolomite has been formed by the replacement of limestone by magnesium salts contained in circulating ground water after emergence of the limestone from the sea, such a process could hardly account for the origin of great thicknesses of uniformly dolomitized formations.

CHAPTER IV

CALCITE-DOLOMITE DIFFERENTIATION BY LABORATORY METHODS

GENERAL STATEMENT

Because of the homogeneous nature of most of the rocks in the section, some difficulty was encountered in determining lithological variations for a stratigraphic column. Most of the limestone was found to be a mixture of calcite and dolomite in which the proportion of each mineral was variable from one horizon to the next. It was therefore necessary to find some means of making quantitative determinations of calcite and dolomite in the samples containing such a mixture.

SUMMARY OF METHODS

Various methods of differentiating between calcite and dolomite have been reported, all of which in principle are based on two facts.

(1) Calcite and dolomite have different chemical properties. Certain reagents which attack calcite do not react with dolomite, or else they do so at a different rate. For example, calcite is much more soluble than dolomite in cold dilute hydrochloric acid.

(2) Gradations between calcite and dolomite do not occur. If isomorphism between the two minerals

was complete, stain tests would not be a sharp index of composition.

Not all the known tests were found to be applicable in testing the samples collected by the writer. Several difficulties had to be overcome before a satisfactory procedure was developed. Most of the tests previously reported have been devised for use on light colored rocks of fairly coarse grain size, in which the results of testing could be observed on hand specimens. Since the samples collected by the writer were nearly all dark grey or black and very fine grained, stain tests on hand specimens were not practicable.

The oldest and simplest method of differentiating between calcite and dolomite is by the application of cold dilute hydrochloric or acetic acid. The acid attacks the calcite but not the dolomite. The method is of limited application in fine grained rocks, but the writer was able to use it in a general way to determine the relative amounts of calcite and dolomite in a sample by the degree of effervescence observed upon application of a drop of dilute hydrochloric acid. For detailed quantitative work this method is of practically no value.

The first attempt to use stains to distinguish calcite from dolomite was made by Lemberg, who used a solution of ferric chloride ($FeCl_3$) (Rodgers, 1940, p. 789). This reacted with calcite and left a coating of ferric

hydroxide ($Fe(OH)_3$), which was converted to black iron sulphide by subsequent treatment with ammonium sulphide ($(NH_4)_2S$). This is known as Lemberg's iron hydroxide stain, or more commonly as the black Lemberg stain.

Lemberg also reported a stain using aluminum chloride ($AlCl_3$) instead of ferric chloride (Rodgers, 1940, p. 789). In this test the calcite becomes coated with colorless aluminum hydroxide ($Al(OH)_3$) which is stained red by logwood dye. This method was not used because the test takes a comparatively long time and also because the solutions used are not stable.

Ross (1935, p. 8) obtained satisfactory calcite stains by using a cold solution of copper nitrate ($Cu(NO_3)_2$) in which the specimen was immersed for several hours. Subsequent washing with ammonium hydroxide produced a deep blue stain of ammoniacal copper hydroxide ($Cu(NH_3)_4(OH)_2$) on the calcite, leaving the dolomite white. This method was investigated but proved impractical in testing the rocks collected by the writer because of the long time required for the test. Moreover, the blue stain was not easily distinguished on specimens that were inherently dark grey in color.

METHODS ADOPTED FOR LABORATORY INVESTIGATION

After experimenting, the writer found a modification of Lemberg's iron hydroxide stain test, suggested by

Fairbairn[1] and reported by Keller and Moore (1937, p. 949), to be quite applicable to the problem at hand. Keller and Moore used the test on polished surfaces and on drill cuttings of limestone, and the writer encountered no difficulty in further modifying their procedure for use on very small particles in immersion mounts, observed under a binocular microscope.

According to this method, two solutions are used. The first is ferric chloride made up to about 2½% strength by weight. The second is ammonium sulphide saturated with hydrogen sulphide (H_2S). The writer found ammonium polysulphide ($(NH_4)_2S_x$) easier to obtain and equally as good.

The rock specimen is first wetted with water, then immersed in ferric chloride for 5 to 10 seconds. Next it is washed thoroughly with water to remove excess ferric chloride. It is then immersed for a similar period in ammonium polysulphide solution and finally washed again with water to remove excess reagent. This completes the test. The calcite stains black, whereas the dolomite is not affected and remains clear. Intergrown angular grains of calcite and dolomite are sharply marked, and minute particles of calcite are vividly shown. Grains of

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(1) H. W. Fairbairn, "Introduction to Petrofabric Analysis", p. 31. Mimeographed copy, Queen's University, Kingston, Canada.

quartz or chert are not stained by the treatment. Confirmation of the test was made by treating specimens of pure calcite and pure dolomite and the results were found to be reliable.

The reactions involved are as follows. Ferric chloride hydrolyzed to produce ferric hydroxide and hydrochloric acid. The acid is very dilute and attacks the calcite but not the dolomite. Neutralization on the calcite surface leaves a concentration of ferric hydroxide, which is converted into black ferric sulphide by the ammonium polysulphide.

The writer found that satisfactory results could be obtained by grinding the samples to a fine size and observing the results of the treatment under a binocular microscope. The fine grained nature of the rocks made magnification necessary for observation of results, and it was found also that fine particles of the dark colored rocks were sufficiently clear and light colored under magnification to allow the staining to become apparent. Material of between 0.25 mm. and 0.105 mm. in size was found best for the test. Particles smaller than 0.105 mm. tended to float on the solutions during treatment and were hard to wash. On the other hand, grains of 0.25 mm. were quite large enough to show the results of treatment.

The procedure adopted by the writer is as follows. The sample was crushed and screened to the required size

(0.25 mm. to 0.105 mm.). A portion of the ground material was set aside in a small bottle for later petrographic examination for quartz and other minerals. Another small portion was used to make a water-immersion mount for comparison with the stained material. The remainder was tested, the tests being carried out in a small evaporating dish. First the sample was washed with water, then treated with ferric chloride for 5 to 10 seconds. Following this it was washed thoroughly with water and then treated with ammonium polysulphide for 5 to 10 seconds, and finally washed again with water. The washing was done by repeated decantation. When tested, the material was mounted with a drop of water on a slide and examined under a binocular microscope with a water-immersion mount of unstained material for comparison. A white porcelain plate under the slides on the stage of the microscope facilitated the examination. A grain count of stained and unstained particles served to determine accurately the relative amounts of calcite and dolomite.

The procedure as outlined above has several advantages.

(1) It takes but little time. The staining occurs almost instantaneously, and several tests can be completed in a few minutes.

(2) The test is definite and conclusive. Distinct

color contrasts are developed, even in the smallest particles.

(3) Solutions used are easily prepared, and they are stable.

(4) Tested samples can be easily observed and determined in simple mounts.

The following disadvantages must also be considered, although for the purpose of this report they are unimportant.

(1) The black iron sulphide is stable for only an hour or so after the test is made. It will oxidize, turn light brown and crumble.

(2) The stain rubs off easily.

Staining Procedure with Thin Sections

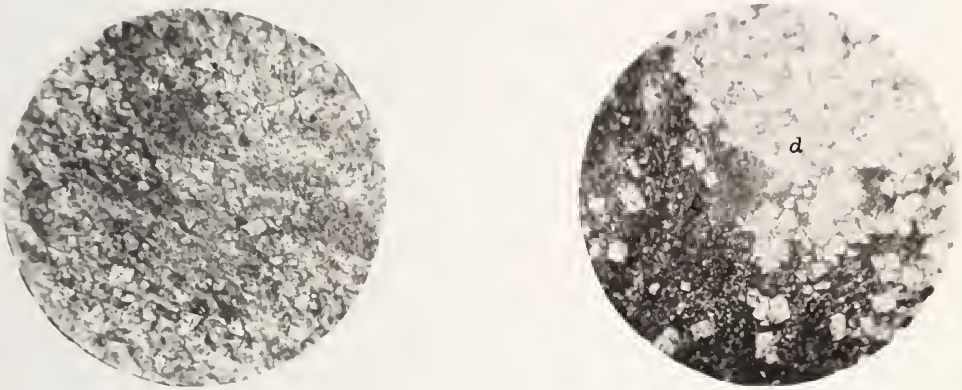
Besides the method outlined above, the writer obtained very satisfactory results by using the stain test on thin sections which could be observed under a petrographic microscope. The sections were ground to standard thickness and mounted without cover glasses. This enabled petrographic examination both before and after staining. The staining procedure for the thin sections was similar to that employed in testing the finely-gound material. The slides were wetted with water, then immersed for 5 to 10 seconds in the ferric chloride solution, washed, then immersed in the ammonium polysulphide

Figure 4. Photomicrograph showing results of stain test on mottled limestone.

A. Mixture of calcite and dolomite, unstained.
B. Interpenetration of calcite (c) and dolomite (d) as shown by stain test.

Figure 5. Photomicrograph showing results of stain test on slightly dolomitized limestone.

A. Mixture of calcite and dolomite, unstained.
B. Same as A after staining, showing rhombohedrons of dolomite (d) embedded in a fine calcareous matrix.



A B

Figure 4
(x 35)

A B

Figure 5
(x 35)

for 5 to 10 seconds, and finally washed again. By means of the stain test the relations between the dolomite patches and the surrounding rock could be plainly seen, and in some cases individual rhombohedrons of dolomite were found to exist in parts of the rock that showed no visible mottling (figs. 4, 5).

CHAPTER V

LITHOLOGY OF THE CAMBRIAN SECTION

GENERAL STATEMENT

The section measured by the writer is composed of a series of limestones, dolomitic limestones and dolomites. With the exception of three fifty-foot bands of very pure limestone which occur in the lower half of the section, the rock consists mainly of partially dolomitized limestone which is very homogeneous in appearance. In some places dolomitization is almost complete, while at other horizons dolomitization has reached only incipient stages. Because of the difficulty involved in determing quantitatively the variations in composition by means of hand specimens, detailed chemical and micro-chemical work was necessary before the lithological units in the section could be worked out in sufficient detail to enable a lithological column to be tabulated.[1]

LITHOLOGICAL COLUMN

The following table, embodying the results of laboratory investigation as well as observations made in the field, shows the lithological units in the section:

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[1] Chemical analyses by J. A. Kelso, Director Industrial Laboratories, University of Alberta.

DEVONIAN

Lower Minnewanka formation (overlying Middle Cambrian)

Dolomite: Massive, dark grey, saccharoidal; contains fine structureless corals.

CAMBRIAN

	feet
Limestone: thin-bedded, dark grey, fine grained; slightly arenaceous; stain test shows over 90% calcite..................	47
Dolomite: soft, arenaceous, light buff colored; weathers buff; tends to assume a shaly habit; contains two thin glauconitic bands...........................	18
Dolomite: fine grained, light grey, saccharoidal; shows no effervescence with cold dilute HCl; chemical analysis shows 54.51% $CaCO_3$, 43.43% $MgCO_3$............	22
Dolomitic limestone: mottled due to partial dolomitization; undolomitized portions very fine grained, dark grey; dolomitized patches grey, saccharoidal, irregular in shape...................................	63
Dolomite: almost completely dolomitized; very brittle, finely saccharoidal; weathered surfaces very rough...............	27
Dolomitic limestone: dark grey, buff-weathering, thin-bedded, partially dolomitized; dolomitization tends to follow bedding............................	18
Dolomitic limestone: slightly arenaceous; effervesces slowly with cold dilute HCl; thin-bedded; shaly habit; contains trilobite fragments and brachiopods, and also fuciods near base......................	15
Limestone: thin-bedded, dark grey, very fine grained; weathers light grey; small dolomite patches indicate partial dolomitization; chemical analyses show composition of limestone to be 96.57% $CaCO_3$, 1.43% $MgCO_3$; of dolomite patches to be 56.43% $CaCO_3$, 38.23% $MgCO_3$.............................	110

Dolomitic limestone: very fine grained, brittle, hackly weathering, mottled; dolomite patches lighter grey and slightly coarser.............................. 115

Dolomitic limestone: dark grey, fine grained, saccharoidal; almost completely dolomitized; also contains conspicuous veins of pure dolomite; chemical analysis of vein material shows composition to be 44.39% $MgCO_3$, 55.42% $CaCO_3$.................................... 45

Dolomitic limestone: fine grained, dark grey, mottled; weathered surfaces extremely rough; becomes less dolomitic and more dense toward base........................... 95

Limestone: dense, light colored, very pure; shows slightly porous; sharp contacts above and below................................. 46

Dolomitic limestone: mottled, dark grey, weathers very rough; undolomitized parts fine grained and brittle, dolomite patches more saccharoidal; chemical analyses show limestone portion contains 91.20% $CaCO_3$, 7.20% $MgCO_3$; dolomite patches contain 54.96% $CaCO_3$, 36.26% $MgCO_3$.................. 295

Limestone: very dense, creamy colored; erratically oolitic, slightly porous; sharp contacts above and below; chemical analysis shows $CaCO_3$ content is 97.63%...... 52

Dolomitic limestone: very fine grained, almost black; brittle; mottled due to dolomitization; weathers very rough; dolomitized patches stand out through differential weathering........................ 80

Limestone: (lime kiln) dense, light grey, fine grained, very pure; sharp contacts above and below; chemical analysis shows $CaCO_3$ content is 97.58%..................... 48

Dolomitic limestone: dark grey, fine grained, mottled; dolomite patches lighter colored and slightly coarser in texture............. 63

Dolomitic limestone: partially dolomitized matrix containing flat rounded pebbles of very fine grained black limestone; some secondary dolomite formed along the pebbles.................................... 1

Dolomitic limestone: very homogeneous; rough weathering, dark grey, mottled; shows uniform partial dolomitization; chemical analyses show limestone portions contain 96.61% $CaCO_3$, 1.68% $MgCO_3$; dolomite patches contain 69.15% $CaCO_3$, 28.24% $MgCO_3$.................................. 248

This is the bottom of the exposed section.

Total thickness of Cambrian section exposed 1,627 feet

DOLOMITIZATION IN THE SECTION

Almost all of the dolomite in the section studied by the writer appears to be of pre-emergent origin, and the evidence obtained from a detailed study of the samples collected seems to indicate that dolomitization resulted from replacement of calcium carbonate in the calcareous ooze by magnesium salts in sea water.

Mottling due to dolomitization is prevalent. Both organic and inorganic mottling occur. The organic mottling is restricted to one horizon, and is apparently a result of dolomitized fucoidal markings, which stand out clearly on weathered surfaces. Inorganic mottling is present wherever partial dolomitization has occurred. The dolomite patches which cause the mottling are very irregular in shape, and show no relation to bedding planes

or any other visible influence. On exposed surfaces such mottles are lighter in color than the undolomitized material, and being more resistant, they stand out through differential weathering. On a smoothly ground surface the mottles appear to be slightly more saccharoidal in texture, in contrast to the surrounding rock which is generally extremely fine grained. In thin sections examined under the microscope the difference in structure is very apparent. The dolomitized areas are evenly crystallized, showing rhombohedrons of dolomite embedded in a matrix of very fine material which appears to be the lithified undolomitized calcareous ooze of the ancient sea floor. The interpenetration of dolomitized and undolomitized material is very sharp, and could have been caused only by the action of percolating waters bearing magnesium salts in solution.

In an attempt to prove conclusively that the mottling in these limestones is a result of dolomitization, chemical analyses were made of some of the best samples of mottled limestone. In these samples the mottles could be distinguished easily by the slight difference in color and texture. The hand specimens were mechanically broken down with a small hammer, and the two varieties of material in each sample were separated as carefully and completely as possible by hand picking. Each variety was then analyzed separately to determine the percentage

of calcium and magnesium carbonates present.

The writer is fully aware that complete separation of the two types of material in a sample of mottled rock could not be obtained by the method outlined above. However, this method appeared to be the only practical way to separate the two types of material, and the results obtained indicate that the error involved was small. The results of three such analyses are shown below:

			$\%CaCO_3$	$\%MgCO_3$
(1)	C26-2	Dolomite portion	54.96	36.26
		Limestone portion	91.20	7.20
(2)	C7-2	Dolomite portion	56.43	38.25
		Limestone portion	96.57	1.43
(3)	C44-1	Dolomite portion	69.15	28.24
		Limestone portion	96.61	1.68

As can be seen from the above table, the ratio of calcium carbonate to magnesium carbonate in the dolomite portions of the first two samples is approximately the same as in pure dolomite. In the third sample, although the composition does not approximate that of dolomite, the proportion of magnesium carbonate is still relatively very high. On the other hand, the material surrounding the mottles is composed largely of calcium carbonate, but contains more magnesium carbonate than ordinary undolomitized limestone. This is further indication that the mottling represents an incipient stage of dolomitization. The high content of calcium carbonate in the

dolomitized areas is due to the fact that the crystals of dolomite have formed in a fine calcareous matrix.

All gradations occur from sparsely mottled limestone to almost pure dolomite. Analysis of a sample from a dolomite horizon showed the composition to be 54.41 percent calcium carbonate and 43.43 percent magnesium carbonate. The degree of mottling is an index of the concentration of magnesium salts in the sea water at the time of deposition. The sparsely mottled beds represent periods during which the concentration of salts was not strong enough to cause complete and uniform dolomitization, but strong enough only to initiate the process.

Evidence of cross bedding in some horizons points to a shallow-water environment and favors the idea of lagoonal conditions during deposition. The beds of pure limestone which are found interstratified with partially dolomitized beds probably represent periods during which influxes of normal sea water lowered the concentration of salts in the lagoon and made conditions unfavorable to dolomitization. The abrupt contacts above and below the pure limestone beds are an indication of the narrow margin between conditions conducive to dolomitization and conditions under which dolomitization would not occur.

The exceptional purity of these limestone beds is shown by the following analysis which was made from samples collected from the quarry of the Loder Lime Company.

	per cent
$CaCO_3$	97.58
$MgCO_3$	.58
SiO_2 and insolubles	.37
Iron and aluminum	.53
Sodium and potassium oxides	.95

Although almost all of the dolomite in the Cambrian formations studied by the writer is of pre-emergent origin, there is a small amount of very pure dolomite which occurs in veins and is post-emergent in time of formation. The rock in which the veins occur is itself dolomitic. The veins show no systematic development, but are irregular in shape and variable in width, the largest being about half an inch wide. They are composed of well developed crystals of dolomite which evidently grew inwards from the walls. As shown by the stain test the centre of the veins commonly contains crystals of calcite. Chemical analysis of the vein material shows the carbonate content to be as follows:

	per cent
$CaCO_3$	55.42
$MgCO_3$	44.39
	99.81

This is very close to the composition of pure dolomite. The slightly higher calcium carbonate content is a result of the pure calcite in the centre of the veins.

There is little doubt that the vein dolomite was formed by secondary replacement of calcium carbonate in dolomitic limestone through the agency of magnesium-bearing ground waters percolating along cracks in the rock. There is no proof as to whether the dolomitizing agent was magnesium carbonate or magnesium sulphate, but since the last material to be deposited was calcium carbonate and not calcium sulphate, it is probable that the ground waters contained magnesium carbonate, which was probably derived from the rocks through which the water circulated.

GLAUCONITE

The presence of glauconite grains in the buff colored dolomite band about sixty feet below the top of the Cambrian section is a further indication of the environmental conditions existing at the time of deposition.

Glauconite is a hydrous silicate of potassium, magnesium, aluminum and ferric and ferrous iron. From the time of its discovery over a century ago, the genesis of glauconite has been obscure, and even the most recent investigations have not satisfactorily explained its formation.

Galliher (1935, p. 1351-1365), after studying the deposits of Monterey Bay, California, stated his belief

that glauconite is formed in marine waters by the alteration of biotite. Conditions favorable to glauconization of biotite are (1) alkalinity of the sea water, (2) slow deposition of sediments, (3) absence of currents. In such an environment the biotite, which is in the form of small flakes, swells and becomes spongy. It then loses some aluminum, some potassium and some magnesium, and gains some water. The iron content is mostly oxidized. As a result, glauconite is formed.

More recently, Hendricks and Ross (1941, p. 683-708) have advanced the theory that glauconite is not an alteration product, but is formed in a reducing environment, the potassium and magnesium being derived from sea water and the other constituents from mud.

Whatever may be the processes responsible for glauconization, it is evident that both of the above theories postulate the same environmental conditions for the formation of glauconite, namely, alkaline shallow water with no currents, and slow deposition. These conditions are also favorable to the formation of dolomite.

CHAPTER VI

PALAEONTOLOGY AND STRATIGRAPHY

PALAEONTOLOGY

General Statement

The fossils collected by the writer were found in a 15 foot zone occupying a position 195 to 210 feet below the top of the section. Fossils were also collected from this zone in the summer of 1941 by Mr. M. B. B. Crockford for the Department of Geology, University of Alberta. The specimens were identified by Dr. Charles Deiss, Montana State University, Missoula, Montana. The complete list of fossils found by the writer and Mr. Crockford is as follows:

Brachiopoda
- *Acrothele* cf. *pentagonensis* Bell

Trilobita
- *Coelaspis prima* ? Deiss
- *Ehmania* n. spec.
- *Ehmaniella* n. spec.
- *Elrathina* spec. indet.
- 2 n. gen., one close to *Solenopleurella*
- *Thomsonaspis* or n. gen.

According to Dr. Deiss none of the trilobite species are exactly the same as those already described but the genera are readily recognizable. With the exception of *Ehmaniella*, all of the genera in the collection

have been found in Middle Cambrian formations in northwestern Montana. Ehmaniella has been found in the Middle Cambrian in Utah, and also in the Stephen formation on Castle Mountain, Alberta. The genus Ehmania has never before been reported in the Canadian Rockies. Because most of the genera have only recently been described they are probably not well known, and for that reason it seems advisable to include here their original descriptions.

Descriptions of Trilobite Genera

Genus Coelaspis Deiss

(Deiss, 1939b, p. 78)

Entire dorsal shield unknown. Genus based on several cranidia and associated pygidia.

Diagnosis: Cranidium strongly convex; subquadrate in outline; deeply furrowed; surface minutely granulose. Facial sutures straight across brim; converging slightly to eye lobes; sharply crescentic around eye lobes; then curving sharply outward and backward. Brim wide; convex in front of glabella; anterior two-thirds deeply and acutely concave. Rim wide medially; sharply upturned; slightly concave; narrowed laterally to form spatulate outline of anterior part of cranidium. Marginal furrow wide; broadly rounded; not clearly defined. Preglabellar area subequal in width to rim; sharply inclined forward. Glabella trapezoidal in outline; anterior end truncated or bluntly rounded; length slightly less than two-thirds that of the cranidium. Glabellar furrows wanting. Occipital ring wide medially; flatly convex; without median node or other ornamentation. Occipital furrow narrow; distinct; straight transversely. Eye lobes short; slightly curved; strongly elevated; situated opposite mid-third of glabella. Eye ridges strong; nearly straight; meet dorsal furrows at antero-lateral

corners of glabella. Free cheeks unknown.

Pygidium subrhomboidal; length slightly more than one-half width. Axial lobe acutely rounded transversely; strongly elevated; tapered slightly; posterior end sharply rounded; length nine-tenths that of pygidium. Four axial segments plus terminal section clearly defined. Pleural lobes triangular; much depressed; flattened; pleural and interpleural furrows faintly defined; margin wide; gently concave to flattened, and unfurrowed.

Remarks: The deeply concave brim, the pointed widened and sharply upturned rim, the deep dorsal furrows, the short raised eye lobes, all combined with the short blunt unfurrowed glabella are characteristics which readily separate this form from any other known Middle Cambrian trilobites.

Genotype: *Coelaspis prima* Deiss, n. sp.

Genus *Ehmania* Resser

(Resser, 1935, p. 24, 25)

Diagnosis: Cranidium of a very common type. Glabella tapered, rounded in form, distinctly demarcated by dorsal furrow; glabellar furrows usually very faint. Brim variable in width, with a convex pre-glabellar area and a flat, upturned rim. Eyes moderate in size, not much bowed, situated about the middle of the cranidium. Fixed cheeks about half as wide as the glabella. Free cheeks show suture intra-marginal for some distance and have a stout, short genal spine.

Thorax has 12 to 14 segments in the specimens observed.

Pygidium wide; axis well defined except at rear; up to six or more axial rings are marked out. Pleural lobes very distinctive because both the pleural furrows and grooves are distinctly impressed to the very margin.

Genotype: *Ehmania weedi*, n. sp.

Genus *Ehmaniella* Resser

(Resser, 1937, p. 10)

Diagnosis: Compared to *Ehmania*, *Ehmaniella* is

characterized by the greater width of the cranidium, heavier eye lines, vertical striae on the wider preglabellar area, and a pygidium with fewer segments. The glabella and fixigenes are apt to be granulose or lined.

Genotype: Crephicephalus (Loganellus) quadrans Hall and Whitfield.

Genus Elrathina Resser

(Resser, 1937, p. 11)
(Deiss, 1939b, p. 87)

Diagnosis: Shield elongate, tapered posteriorly. Cranidium subtrapezoidal; flatly to moderately convex. Glabella sub-parallel sided; bluntly rounded to transverse anteriorly. Brim moderate in width. Rim subequal to or narrower than preglabellar area; slightly thickened and upturned. Marginal furrow distinct; rounded. Facial suture intramarginal for short distance; diverging slightly but uniformly backward to eye lobes; then more widely to lateral edge of cranidium; then abruptly backward for short distance to posterior edge. Fixed cheeks wider than brim; postero-lateral limbs strong; relatively wide; possess well-defined rounded, straight furrow.

Thorax tapers backward to pygidium. Axial lobe narrow; rounded; composed of 18 or 19 segments (19 in genotype). Pleural lobes flattened above; bent downward laterally. Pleural lobes strong; rounded; straight. Pleurae straight; uniform in width; with laterally directed, bluntly pointed distal ends.

Pygidium minute; transversely elliptical. Axis sharply tapered; wide; acutely rounded posteriorly. Pleural lobes faintly furrowed. Rim unknown. Posterior edge without spines.

Remarks: The genus is characterized by the posteriorly diverging facial sutures; broad fixed cheeks and postero-lateral limbs; 18 to 19 segments in the uniformly tapered thorax; and by the relatively tiny tail.

Genotype: Concephalites cordillerae Rominger

Genus Thomsonaspis Deiss

(Deiss, 1939b, p. 110)

Diagnosis: Cranidium longitudinally concavo-convex; length slightly greater than width between eye lobes; surface granular; brim marked with longitudinal irregular lines. Glabella subtrapezoidal; length including occipital ring two-thirds that of cranidium; subconical in cross-section. Glabellar furrows moderate to strong; in three pairs; posterior pair strongest. Occipital ring flatly rounded; slightly wider medially. Occipital furrow straight; shallow; broad. Dorsal furrows strong; straight; shallower, but continued, in front of glabella. Three depressions or punctae present in dorsal furrow anterior to glabella; one at each anterior corner of, and one in front of, middle of glabella; scarcely visible on weathered specimens. Brim wide; strongly concave. Rim upturned and slightly thickened. Fixed cheeks moderately wide medially; flatly convex; postero-lateral limbs long, narrow, pointed, and possess deep rounded furrow. Eye lobes raised; thickened, gently curved; located opposite mid-length of glabella. Eye ridges elevated; wide; subangular to rounded; cross fixed cheeks to meet dorsal furrows just back of antero-lateral corners of glabella.

Pygidium transversely elliptical; posterior edge gently curved; anterior edge much more sharply curved; length approximately one-half width. Axial lobe very strong; semicircular in cross-section; tapered slightly; length essentially that of pygidium; width slightly greater than one-third that of pygidium; composed of four segments plus large acutely rounded terminal section. Pleural lobes triangular; flattened; slightly concave in lateral third; marked by four strong subangular segments separated by wide flatly rounded furrows. Surface minutely granular.

Remarks: The narrow glabella with its relatively strong furrows; the wide, concave, tripartite brim; the narrow postero-lateral limbs of the fixed cheeks; the strong eye lobes and ridges; combined with the three punctae in the dorsal furrow anterior to the glabella, readily separate the cranidia of Thomsonaspis from those of any other known genus. The long high strong furrowed axis, the flattened depressed pleural lobes, and the simple strong pleural segments and furrows distinguish the pygidium of Thomsonaspis also from that of any other known genus.

Genotype: Thomsonaspis obscura Deiss, n. sp.

STRATIGRAPHY

Faunal Horizons

The trilobites collected by the writer and Mr. Crockford represent zones in the upper part of the Middle Cambrian faunal succession worked out by Deiss (1940, p. 782) in the Cordilleran region. Of the seven faunal horizons established by Deiss only the upper three were found in the section at Kananaskis. From oldest to youngest these faunal horizons are:

1. The lowest faunal horizon is named from the trilobite Ehmania (Deiss, 1938b, p. 274) which is very prolific in the Lewis and Clark range of northwestern Montana, but which has not previously been reported from the Canadian Rockies. In Montana Ehmania occurs in the uppermost beds of the Pagoda limestone and near the bottom of the overlying Pentagon shale (Deiss, 1939b, p. 79-84). The Ehmania zone in Montana is considered by Deiss to be in the lower part of the Pentagon shale. The zone also occurs in the Meagher limestone in Wyoming and central Montana (Deiss, 1936, p. 1287, 1298, 1314, 1321). Farther south it is found in the Swasey limestone in the House Range, Utah (Deiss, 1938, p. 1134).

The genus Ehmaniella is sometimes found at the same horizon as Ehmania, and appears to occupy the same

position stratigraphically. However, Ehmaniella seems to be more erratic in its distribution. It has not been reported in Montana but occurs in the Ute limestone in the Blacksmith Fork area, Utah, (Deiss, 1938a, p. 1113) and is found along with Ehmania in the Swasey limestone in the House Range, Utah (Deiss, 1938a, p. 1134). Ehmaniella has also been found in the middle part of the Stephen shale on Castle Mountain, Alberta (Deiss, 1939a, p. 967, 973).

2. The second faunal horizon represented in the collection corresponds to the "Agnostus"-Bathyuriscus-Elrathina zone (Deiss, 1939b, p. 63). In a later paper by Deiss this faunal zone is referred to as the "Bathyuriscus-Elrathina fauna which is widespread, but most prolific in the Pentagon shale of northwestern Montana" (Deiss, 1940, p. 784). The stratigraphic position of this zone is in the upper middle part of the Pentagon shale (Deiss, 1940, p. 783). The genus Elrathina was named by Resser (1937, p. 11) from the genotype Concephalites cordillerae (Rominger) which was found in the Ogygopsis shale at the top of the Stephen formation on Mount Stephen, British Columbia.

3. The third faunal horizon, named from the trilobite Thomsonaspis, is represented in the collection by Thomsonaspis and Coelaspis. The genus Thomsonaspis

was formerly included with the <u>Kochaspis upis</u> fauna which was known only in northwestern Montana. In 1938 <u>Thomsonaspis</u> was found in the upper part of the Stephen formation on Castle Mountain, and it was then found possible to correlate the <u>Thomsonaspis</u> zone in the Stephen with the same faunal zone in the Steamboat limestone in northwestern Montana (Deiss, 1940, p. 785). This zone contains the youngest group of trilobites from the Middle Cambrian in the Cordilleran trough. In Montana it occurs near the top of the Steamboat limestone, 225 to 400 feet stratigraphically above the <u>Bathyuriscus-Elrathina</u> zone (Deiss, 1940, p. 785).

The faunal assemblage represented in the collection is puzzling since it contains genera which in Montana are several hundred feet apart. As stated by Deiss[1] "the collection......represents the <u>Ehmania</u> zone and also the <u>Thomsonaspis</u> zone in northwestern Montana". The <u>Ehmania</u> zone occurs in the lower part of the Pentagon shale, and the <u>Thomsonaspis</u> zone occurs in the Steamboat limestone at least 300 feet above.

It is not within the scope of this thesis to attempt to explain the occurrence of these mixed faunal zones, nor would it be logical to do so on the basis of a study which covered only one Middle Cambrian section.

---

(1) Communication to Dr. P. S. Warren, February 6, 1942

The problem is one that can be solved only by extensive field work involving a detailed study of Cambrian formations in the Cordilleran region. For the purpose of this report it is sufficient to know that the beds underlying the Lower Minnewanka formation at the front of the mountains in Bow Valley are Middle Cambrian in age. As no fossils were found in the lower part of the section, nothing definite can be said regarding the age of those beds except that they are lower Middle Cambrian or older.

Correlations

General Statement

Correlations of formations in widely separated areas are sometimes of doubtful value. Formations are lithologic and cartographic units which usually are not uniformly continuous for long distances, and often fossils have no constant relationship to single formations or even to one particular type of rock. It is often assumed that a fauna, once developed, will become universal in the sea in which it lives, but the time factor in the development and particularly in the migration of a particular form is not always considered. Also, it is well known that the sea bottom at the present time is not universally or uniformly populated, but contains areas which support abundant life and other areas that are practically barren. It is as logical to assume that dissimilar faunas can exist a few

hundred miles apart in the same continental sea under different environmental conditions as it is to postulate non-deposition in order to use similar faunal assemblages to indicate equivalent formational time ranges.

In the light of these considerations it is unnecessary to assume that 15 feet of strata in the section measured by the writer at Kananaskis are equivalent to several hundred feet of strata in northwestern Montana, for although the faunas are similar at the two places, the faunal time ranges may be different. However, a comparison of the sections, based on generic similarities of faunas, is entirely logical. The writer therefore feels that the type of correlation chart used by Deiss (1940, p. 783) is well suited for use in this report. In this chart (fig. 6) the relative stratigraphic positions of successive faunal horizons can be indicated, and the formations adjusted to the faunas which they contain. Thus the sections as a whole are correlated but the individual formations are not.

Chart Showing Correlations of
FAUNAL HORIZONS IN MIDDLE CAMBRIAN SECTIONS IN CORDILLERAN TROUGH

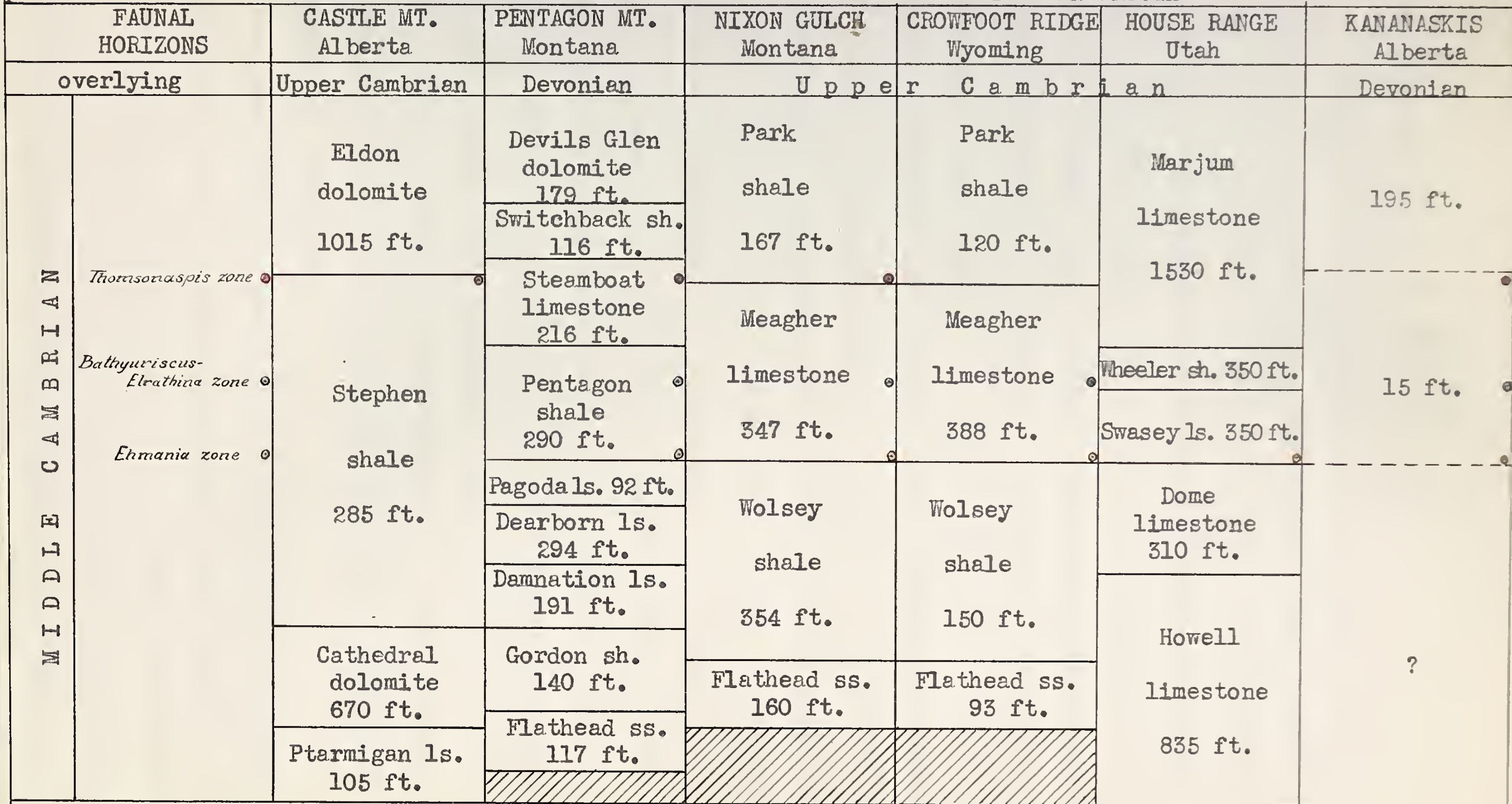

Figure 6. (after Deiss, 1940, p. 783).

Local Correlations

Attempts have been made to correlate the beds immediately underlying the Lower Minnewanka formation along the front of the mountains with the Ghost River formation. The name Ghost River formation was given by Walcott (1923, p. 463) to a series of 285 feet of thin-bedded and shaly buff colored magnesian limestones lying conformably between the Middle Cambrian limestone and the Minnewanka limestone in the front ranges of the Rocky Mountains between the south fork of Ghost river and Red Deer river. Walcott found no fossils in the Ghost River formation and therefore could not definitely determine its exact age, but in a later paper (1928, p. 210) he describes the formation as Devonian, occurring immediately above the great "Ghost River Interval", and subjacent to massive Middle Devonian limestones. In the Banff area, Warren (1927, p. 14) found the Ghost River formation to be 300 feet thick, and, lacking fossil evidence, inferred that it was Devonian on the basis of lithology and on account of its conformable position below the Lower Minnewanka limestone.

Beach[1] questions the advisability of applying the term Ghost River to the beds immediately beneath the Lower Minnewanka limestone at the front of the mountains

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(1) Personal communication, December 20, 1941.

south of Bow valley. In measuring sections at three places along the front of the mountains between Bow valley and the south end of the Moose Mountain area, Beach was able to determine a lithologic unit as yet undescribed, about 260 to 300 feet thick, underlying the Lower Minnewanka limestone and containing specimens of a Middle Cambrian trilobite identified as <u>Oldhamnia</u>.* A thickness

* In a communication received by the writer on April 16, after this thesis had been submitted, Dr. Beach states that the name of this trilobite is not <u>Oldhamnia</u>, but <u>Ehmania</u>. Consequently it may be assumed that the lithologic unit determined by Beach corresponds roughly to the upper 300 feet of the section measured by the writer.

300 feet are dolomitic, grey in color, weather light grey to buff. On the basis of lithology these beds might be correlated with Walcott's Ghost River formation. The thickness, the dolomitic nature, and stratigraphical position of the three units all correspond fairly closely with the Ghost River formation as described by Walcott. On the other hand, fossil evidence proves beyond a doubt that the beds underlying the Devonian in Bow valley are Middle Cambrian. If these beds are called Ghost River, then Walcott's type section of the Ghost River formation must also be assigned to the Middle Cambrian instead of the Devonian. Until more detailed work has been done on Walcott's type section of the Ghost River formation its age cannot be stated definitely. However, in the opinion of the writer the term Ghost River should not be applied

to the beds underlying the Lower Minnewanka limestone at the front of the mountains in Bow valley.

Cambrian-Devonian Hiatus

In the section studied by the writer, lithological evidence indicates that the Cambrian-Devonian contact lies at the base of the Lower Minnewanka formation, 195 feet above the trilobite horizon. The writer was unable to detect any sign of an unconformity beyond the fact that a sharp lithological change occurs at this point.

Walcott (1928, p. 198), who studied the section at the front of the mountains on the south fork of Ghost river about 12 miles to the north, realized that the sedimentary record of a long period of time was missing, and named the break the "Ghost River Interval", but he found no unconformable strata between the Middle Cambrian and the Lower Minnewanka formation. So far as is known to the writer, no direct evidence of an unconformity representing the interval between Middle Cambrian and Middle Devonian time has ever been reported.

No definite conclusions regarding the nature of the hiatus can be drawn from a study of one section along the front of the mountains. The solution of this problem awaits the attainment of a comprehensive knowledge of palaeogeography and sedimentation in the Cordilleran trough, particularly in the central and northern parts.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The section exposed below the Lower Minnewanka formation at the front of the mountains in Bow valley was examined and measured, and rock samples were collected. The total thickness of the section, as computed from measurements, is 1,627 feet.

The lithology of the rocks below the Lower Minnewanka formation was studied in detail with particular reference to the origin of the dolomite which they contain. Staining tests were employed in the laboratory to differentiate between calcite and dolomite, thus enabling quantitative determinations to be made of the relative amounts of each substance present. It was concluded that almost all of the dolomite found in these rocks was formed on the sea floor, probably in a protected lagoon where the water was shallow and the salts were more highly concentrated than in ordinary sea water. The initial step in the formation of dolomite would be replacement of calcium carbonate in the unconsolidated sea-floor sediments by magnesium carbonate derived from sea water. Mottling in the limestone represents partial dolomitization, indicating that the concentration of salts was low or that deposition of sediments and subsidence of the sea floor went on too quickly to allow complete and uniform dolomitization to take place. A very small proportion of

the dolomite in the section was formed by processes which were active after the consolidated rocks had emerged from the sea. Dolomite of this type is very pure and is found in irregular veins, which indicates that it was probably deposited from magnesium-bearing ground waters percolating along cracks in the limestone.

The fossils collected from the section consist of trilobite fragments, brachiopods and fucoidal markings, which were found in a 15-foot horizon lying 195 to 210 feet below the base of the Lower Minnewanka formation. The trilobites in the collection represent three faunal horizons which in northwestern Montana are found ranging through approximately 500 feet of beds. Two of these faunal horizons have not previously been reported in Canada. The presence of these Middle Cambrian fauna in a zone 195 feet below the Lower Minnewanka formation indicates either that the Ghost River formation is not present at the front of the mountains in Bow valley or that the type section of the Ghost River formation as defined by Walcott is not Devonian, but Middle Cambrian in age. The writer is not prepared to state which of these two alternatives is actually the case. However, in the opinion of the writer, until the type section of the Ghost River formation has been studied in detail and if possible traced southward, the term Ghost River should not be applied to the beds immediately underlying the Lower Minnewanka

formation at the front of the Mountains in Bow valley.

On the basis of the lithological character of the rocks lying between the trilobite zone and the Lower Minnewanka formation, the writer has concluded that the Cambrian-Devonian contact at the front of the mountains in Bow valley should be drawn at the base of the massive black saccharoidal coral-bearing dolomitic limestone of the Lower Minnewanka formation. The hiatus between the Middle Cambrian and the Middle Devonian is not apparent. No indication of an erosional or angular unconformity was found.

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